Limestone, Gypsum, and Magnesium Oxide Influence Restoration of an Abandoned Appalachian Pasture

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ABSTRACT

When restoring abandoned pastures on acidic hill-land soils to productivity, it is important to bring soil Ca and Mg to adequate levels. Gypsum is a readily available Ca amendment that is sufficiently soluble to move rapidly into the soil when surface-applied. Gypsum has been shown to reduce detrimental effects of subsurface acidity in soils of the southeastern USA. A 4-yr experiment was initiated to measure effects of surface gypsum application on forage production and to evaluate Mg-containing amendments to avoid gypsum-induced Mg deficiency. The study site was a southern West Virginia Gilpin silt loam (fine-loamy, mixed, mesic, Typic Hapludult) where abandoned hill-land pasture was being restored to productivity. Treatments included 0, 1000, 8000, 16 000, and 32 000 kg/ha flue gas desulfurization coal combustion by-product gypsum (gypsum) together with dolomitic limestone and five additional treatments to evaluate sources of supplemental Mg. Application of 16 000 kg/ha gypsum together with limestone increased forage yields of mixed orchardgrass (*Dactylis glomerata* L.) and tall fescue (*Festuca arundinacea* Schreb) pasture during establishment by 42% and production by 11% compared with limestone alone. About 8% of the mean 790 kg/ha yield increase could be attributed to acidity-neutralizing effects of alkaline constituents in the gypsum by-product. Plants in higher gypsum treatments had higher concentrations of K and P, but gypsum application decreased soil and plant Mg concentrations. This indicated that gypsum should not be applied on typical acid soils without supplemental Mg.

PASTURE LAND requiring renovation is typically characterized by a recent history of low or zero inputs of fertilizer and agricultural limestone. Because of continual leaching losses of Ca and Mg in Appalachia due to precipitation, restoration of pastures requires establishing adequate Ca and Mg in the rooting zone of newly established forage species.

In steep or stony pastures, surface application of liming agents is often the only economically viable option for adding Ca and Mg and increasing soil pH. However, improvements in subsurface soil pH from surface application of dolomitic limestone occur slowly, unless very high rates are applied (Cregan et al., 1989).

Gypsum ($CaSO_4{\cdot}2H_2O$) is a source of Ca and S that can move quickly into the subsoil, and thus represents a potentially valuable input for rapidly recharging the soil profile with Ca. Large amounts of relatively pure gypsum are becoming increasingly available in the eastern parts of the USA as by-products from desulfurization of coal-fired power plant emissions. In 1998, the U.S. power industry generated 12×10^6 t of gypsum and gypsum precursors (ACAA, 1999). By-product scrubber gypsum generated for use in manufacturing wallboard contains relatively little $CaCO_3$, but mined agricultural gypsum commonly incorporates 15% total $CaCO_3$ and SiO_2 and can contain up to 45% nongypsum materials (Weist et al., 1994; Ritchey et al., 2000).

Gypsum does not affect soil pH as much as limestone does, but because of the large amounts added, gypsum induces major changes in the suite of exchangeable ions, increasing Ca, S, and Mn and generally reducing levels of K and Mg (Ritchey et al., 1995). In soils of the Georgia Piedmont, applying 10 000 kg/ha gypsum increased subsurface soil pH by 0.1 unit, reduced KCl-extractable Al by 30%, and increased alfalfa (*Medicago sativa* L.) yields by 25% (Sumner et al., 1986). Soil improvements and increased yields have persisted 16 yr (Toma et al., 1999). The pH increase apparently is caused by release of hydroxides from oxidic Fe and Al minerals in exchange for SO_4 anions. Part of the phytotoxic Al not precipitated by increases in pH may form soluble aluminum sulfate complexes that are nontoxic (Kinraide and Parker, 1987). In Appalachian soils, some additional benefits of gypsum application may result from leaching of Al from the profile (Wendell and Ritchey, 1996) and from increases in the exchangeable Ca/Al ratio.

Positive responses to gypsum application on acid soils in the Northeast have generally been observed with deep-rooted legumes. Stout and Priddy (1996) increased alfalfa yields 21% by applying 18 000 kg/ha gypsum. They attributed the increased yield to lower moisture stress, probably due to deeper roots, especially at the 45-cm depth where the soil Ca/Al ratio increased by approximately 45% compared with untreated soil. There are few reports of benefits on nonleguminous Appalachian pastures. Because abandoned pasture soils are particularly likely to be low in Ca and Mg, and beneficial results of surface-applied limestone move downwards slowly, we wanted to evaluate whether the greater solubility of gypsum would be helpful in early phases of pasture renovation.

The objectives of this field experiment were to (i) determine beneficial and detrimental soil changes arising from by-product gypsum addition; (ii) evaluate changes in forage botanical composition, plant mineral concentrations, and yield; (iii) estimate both the yield improvement due to contributions of liming agents present in

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Abbreviations: pH_s, pH in 0.01 *M* calcium chloride; TCE, total calcium carbonate equivalency.

Table 1. Treatments surface-applied to an infertile abandoned Appalachian pasture on Gilpin loam (Typic Hapludults) soil in southern West Virginia as part of a larger experiment to evaluate amendment effects on establishment and production of tall fescue and orchardgrass forage. The first five treatments provide a gypsum response profile under limed conditions, and the second group examines contrasts without limestone.

Treatment abbreviation	Gypsum no. 22†	Gypsum no. 27‡	Dolomitic limestone	MgO fertilizer	Total Mg added	Amendment TCE§
	kg/ha					
G_0L	0	0	4 650	0	512	4 840
G_1L	1 000	0	4 650	0	512	4 890
G_8L	8 000	0	4 650	0	514	5 240
$G_{16}L$	16 000	0	4 650	0	516	5 640
$G_{32}L$	32 000	0	4 650	0	519	6 440
G_0	0	0	0	0	0	0
G_0MgO	0	0	0	526	268	1 290
G_8	8 000	0	0	0	4	400
G_8MgH‡	0	8 480	0	0	195	1 110
$G_{16}MgO$	16 000	0	0	526	272	2 090

† Wallboard quality agricultural gypsum produced by a limestone-based, in situ oxidation, wet-scrubber desulfurization system.
‡ Experimental gypsum product containing 23 g/kg Mg as $Mg(OH)_2$.
§ TCE, total $CaCO_3$ equivalency. All of the amendments had some potential to neutralize soil acidity. The $CaCO_3$ equivalency values ranged from 5% for by-product gypsum up to 245% for MgO fertilizer (Table 2). We calculated the TCE per treatment by summing the neutralizing capabilities of each amendment component as calculated by multiplying the $CaCO_3$ equivalency of the component by the quantity of that component included in the treatment.

by-product gypsum and the yield improvement due to contributions from the $CaSO_4$ component; and (iv) evaluate various approaches for maintaining adequate Mg levels in gypsum-treated soils.

MATERIALS AND METHODS

A site in southern West Virginia (37°48′45″ N, 80°58′45″ W) that had been abandoned for three decades and then rotary-mowed annually for10 yr, but not otherwise used, was selected as representative of abandoned farmland in the region. Grasses of low nutritive value, primarily red fescue (*Festuca rubra* L.), poverty grass (*Danthonia spicata* L.), and broom sedge (*Andropogon virginicus* L.), covered 28% of the area. Broadleaf weeds were present on 66% of the pasture, with goldenrod (*Solidago juncea* Ait.) as the most prevalent. The soil on the site is a Gilpin silt loam (fine-loamy, mixed, mesic, Typic Hapludult). Plots (8 by 3 m) organized in a randomized complete block design with four replications were laid out on a well-drained hillside with 8 to 15% slope.

Treatments (described in detail in Table 1) included five levels of gypsum applied with dolomitic limestone to measure effects of gypsum on forage yield (G_0L, G_1L, G_8L, $G_{16}L$, and $G_{32}L$), and five treatments to evaluate additional sources of Mg (G_0, G_0MgO, G_8, G_8MgH, and $G_{16}MgO$). We chose gypsum rates to cover the range most likely to be used by farmers. Properties of amendments as determined by Clark et al. (1995a) are given in Table 2.

In July 1993, fertilizer (33, 58, and 110 kg/ha N, P, and K, respectively) was surface-applied as were treatments of dolomitic limestone, lightly calcined magnesite MgO fertilizer (Fert-o-Mag, American Minerals, Wilmington, DE),[1] and agricultural gypsum produced as a wet-scrubber by-product of a coal-fired power plant. Treatment G_8MgH, an experimental $Mg(OH)_2$–supplemented gypsum (College et al., 1997) formulated to contain 5 to 6% $Mg(OH)_2$, and a comparison treatment of agricultural gypsum (G_8) were applied in April 1994. Fertilizer amounts (kg/ha) surface-applied subsequently were 38 N in 1994; 97 N, 99 P, and 221 K in 1995; 237 N, 28 P, and 54 K in 1996; and 223 N, 59 P, and 112 K in 1997. Nutrient sources used were NH_4NO_3; KCl; triple superphosphate; and 19–19–19, 0–25–25, and 5–20–20 fertilizers. Sulfur-free fertilizers were utilized to allow evaluation of possible beneficial nutritive effects of S contained in gypsum.

The area was rotary-mowed and then seeded in April 1994 with 'Canvy' Kentucky bluegrass (*Poa pratensis* L.) at 3 kg/ha, 'Potomac' orchardgrass at 8.7, and 'KY31' tall fescue at 10.9 using a Brillion seeder (Brillion Iron Works, Brillion, WI) to simulate frost seeding. Because these species did not establish, the area was reseeded July 1994 with a no-till pasture renovator using rates of 13.4 kg/ha 'Abel' orchardgrass, 10.5 of KY31 tall fescue, and 4.3 of Canvy bluegrass. To improve stands, another seeding was made in February 1995 with 19.7 kg/ha Abel orchardgrass and 20.9 kg/ha KY31 tall fescue and in March 1995 with 14.1 kg/ha Canvy bluegrass. Because the stand was still poor, we applied dicamba (dimethylamine salt of 2-methoxy-3,6-dichloro-*o*-anisic acid) herbicide to reduce broadleaf growth on 24 May and 10 July 1995 at 7.0 L/ha.

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-ARS.

Table 2. Chemical and physical properties [Ca, Mg, and S concentrations; $CaCO_3$ equivalents (CCE); and particle size distribution] of amendments surface-applied to a Typic Hapludults infertile abandoned pasture soil in southern West Virginia. In treatments G_0MgO and $G_{16}MgO$, MgO fertilizer (Fert-o-Mag) was used to supply Mg.

Amendment	Elemental concentration			CCE	Particle size distribution		
	Ca	Mg	S		<0.125 mm	0.125–0.250 mm	>0.250 mm
	g/kg			g/100 g			
Dolomitic limestone	210	110	0	104	17	37	46
MgO fertilizer	0	510	0	245	†		
By-product gypsum no. 22‡	238	0.23	216	5	25	46	29
Mg-enhanced by-product gypsum no. 27‡	209	23	177	13	74	22	4

† Particle size range for MgO fertilizer (Fert-o-Mag) is 1 to 2.8 mm to allow blending with granulated fertilizers.
‡ This and additional information about by-product gypsums no. 22 and 27 is given in Clark et al. (1995a).

Yield was evaluated by clipping a 4.3-m^2 area in the center of the plots to 5-cm height. After harvest, remaining forage was cut and removed. During establishment (Phase I), two harvests per year were made (23 June and 19 Sept. 1994 and 14 June and 21 Aug. 1995). During the production stage (Phase II), three harvests per year of the fully renovated pasture were made (3 June, 17 July, and 25 Sept. 1996 and 10 June, 4 Aug., and 3 Oct. 1997).

Botanical composition was determined by characterizing the principal species present at 20 or 30 locations within plots, as selected by throwing a meter stick at random onto plots, or using a point-quadrat method with 20-cm intervals within a 1-m^2 area. Botanical composition was measured on 22 June 1994, 17 Aug. 1995, 8 Aug. 1996, and 7 May 1997.

Forage dry matter percentages were determined from oven-dried samples (36 h at 67°C). Subsamples for mineral analysis from all harvests except one in Phase I and one in Phase II were ground to pass a 0.5-mm screen, and 50 to 100 mg was weighed into 23-mL Teflon containers and microwave-digested with an acidic solution (1.7 mL 15.8 *M* HNO_3 + 0.2 mL 11.4 *M* HCl + 0.1 mL 28.9 *M* HF) for 4 min at 70% power followed by 2 min at full power (635 W delivered) as modified from Kingston and Jassie (1988). Solutions were brought to final volumes of 10 mL by adding water and analyzed by inductively coupled plasma emission spectroscopy. Total S and N were measured by high-temperature combustion with a LECO CHN-600 instrument (Leco Corp., St. Joseph, MI). Yearly mean nutrient concentrations were averaged to obtain forage mineral concentrations for Phase I and Phase II.

Soil samples to 45-cm depth were collected in 15-cm increments in September 1994, October 1995, October 1996, and November 1997. Soil analyses consisted of measuring neutral 1 *M* ammonium acetate–extractable Ca, Mg, K, and S (Thomas, 1982); KCl-extractable Al (Barnhisel and Bertsch, 1982); pH in 0.01 *M* $CaCl_2$ (pH_s); and electrical conductivity (1:1 soil/water).

Analysis of variance and regression evaluations were conducted using General Linear Model statistical procedures (SAS Inst., 1990). Yearly yields were calculated by summing individual harvests. Because year × treatment interactions were not significant for yield within the 2 yr comprising the establishment phase (Phase I) and within the 2 yr comprising the production phase (Phase II), results are presented as means for each phase. When the analysis-of-variance *F*-test was significant at the 0.05 probability level, LSD values were

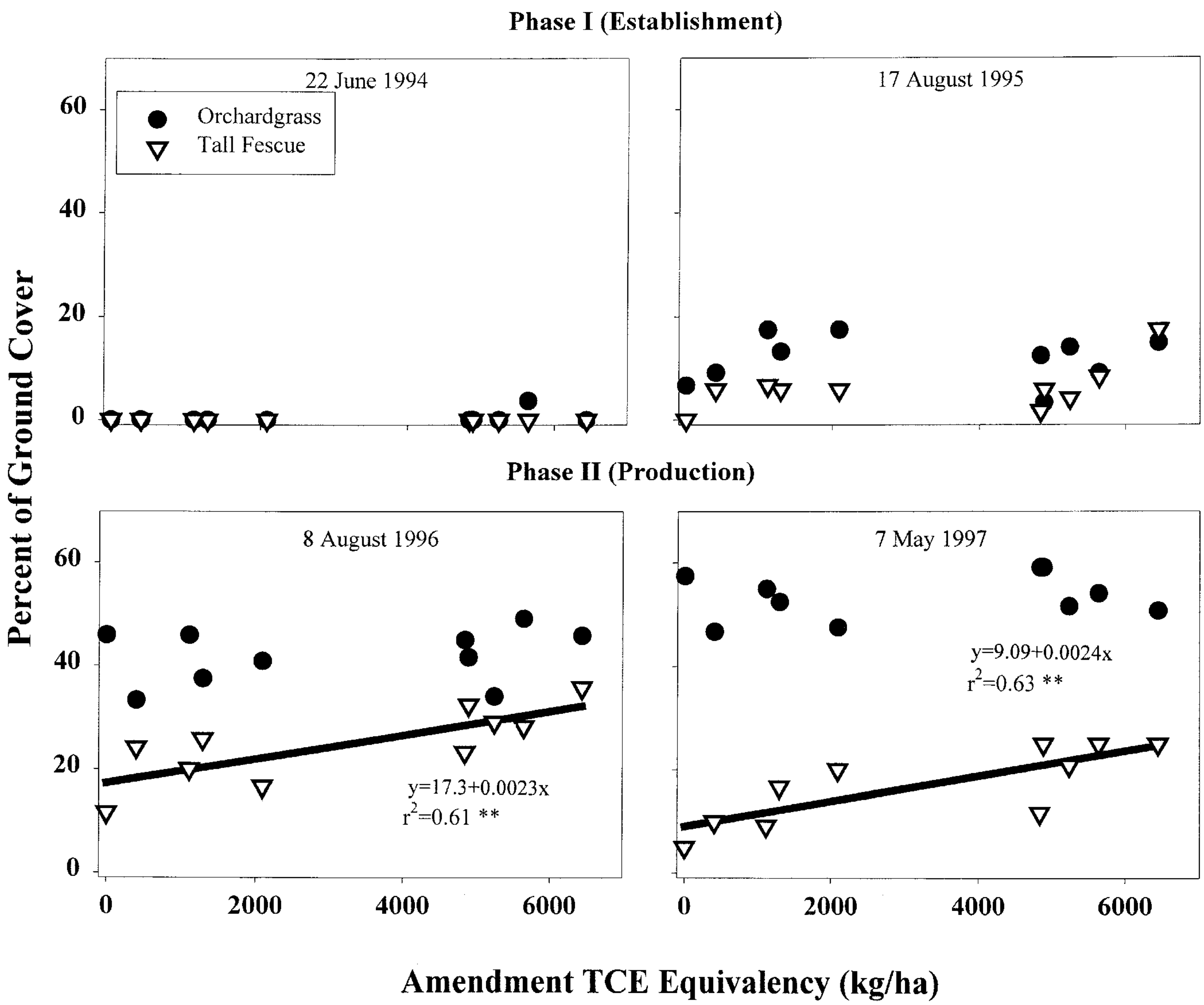

Fig. 1. Prevalence of tall fescue and orchardgrass during establishment (Phase I) and production (Phase II) as a function of total $CaCO_3$ equivalency (TCE) of amendments surface-applied to an abandoned Appalachian pasture. Coefficient-of-determination significance of $P <$ 0.01 indicated by **.

Table 3. Monthly precipitation during 1994–1995 (Phase I—establishment) and 1996–1997 (Phase II—production) near Bragg, WV.

Month	1994	1995	1996	1997	30-yr avg.
	Precipitation, mm				
1	99	147	125	48	74
2	128	61	46	40	75
3	157	49	108	169	86
4	70	54	63	80	87
5	105	184	234	119	101
6	59	115	113	14	98
7	201	47	126	99	119
8	182	62	138	49	86
9	30	104	164	42	85
10	44	94	65	26	73
11	37	88	77	73	76
12	52	54	102	34	82
Total	1164	1059	1361	793	1042

calculated to test differences between means. All differences and regressions discussed are significant at the 0.05 probability level unless otherwise stated.

RESULTS AND DISCUSSION

Precipitation

Variation in precipitation during the 4 yr of the experiment was within normal limits for the region (Table 3). Precipitation in 1994 and 1995 (Phase I) was 12 and 2% greater than the 30-yr average, respectively. In 1996 and 1997 (Phase II), precipitation was 31% greater than and 24% less than the 30-yr average, respectively.

Botanical Composition

At the initiation of Phase I (orchardgrass and tall fescue establishment), botanical composition reflected the original plant population, which was typical of low-fertility, low-management abandoned pastures in the region. With the use of herbicide and continued fertilizer application, seedlings of orchardgrass and tall fescue were finally established, but bluegrass was not detected.

In the production stage (Phase II), tall fescue and orchardgrass dominated the sward (Fig. 1). The proportion of tall fescue was positively related to total $CaCO_3$ equivalency (TCE) of the applied amendments while the percentage of orchardgrass was constant (Fig. 1).

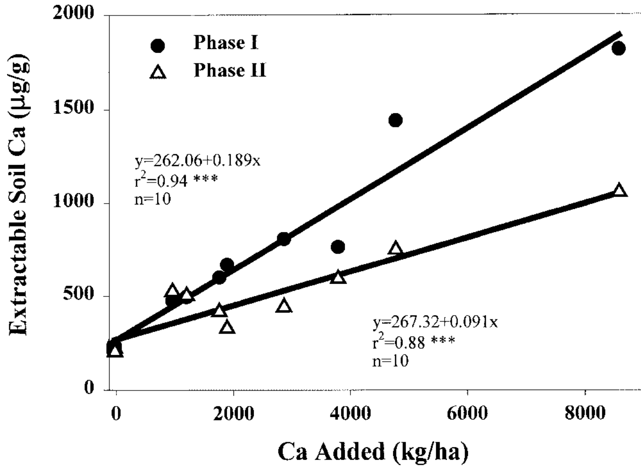

Fig. 2. Soil Ca (0–15 cm) during establishment (Phase I) and production (Phase II) of tall fescue and orchardgrass forage as affected by total amount of Ca added to a Typic Hapludults soil in southern West Virginia. Coefficient-of-determination significance of $P <$ 0.001 indicated by *.**

This is consistent with data presented by Clark et al. (1997), showing greater responses to lime addition by tall fescue than by orchardgrass in a similar Typic Hapludult from southern West Virginia.

Effects on Soil and Forage Mineral Element Composition

Calcium

Soil Ca was strongly affected by amount of Ca added (Fig. 2). The level of soil Ca originating from added gypsum present in the 0- to 15-cm layer in Phase II dropped to half that present in Phase I, probably due to movement of Ca deeper into the soil profile (Fig. 2). Plant removal of Ca was <40 kg/ha Ca, or 7% of the mean decrease in soil Ca.

Mean plant Ca concentrations were proportional to soil Ca saturation [Ca/(Ca + Mg + K + Al)] in both Phase I and Phase II (statistical significance of correlations referred to in the text are given in Tables 4 and 5), but they never reached excessive levels. We used plant

Table 4. Statistical significance of regressions among soil parameters during Phase I (establishment) and Phase II (production) for a Typic Hapludults soil in southern West Virginia receiving surface-applied treatments of gypsum, limestone, and MgO.

y	*x*	Phase	Relationship	*n*	r^2	*P*
Al, µg/g	pH_s†	I–II	$y = 1190 - 240x$	20	0.95	<0.0001
Al, µg/g	TCE,‡ kg/ha	I–II	$y = 228 - 0.02x$	20	0.84	<0.0001
S, µg/g	EC,§ dS/m	I–II	$y = 29.2 + 246x + 1109x^2$	20	0.93	<0.0001
S, µg/g	Ca, µg/g	I–II	$y = 69.9 - 0.122x + 0.00036x^2$	20	0.92	<0.0001
S, µg/g	Gypsum rate, kg/ha	I	$y = 29.9 + 0.0304x$	10	0.94	<0.001
S, µg/g	Gypsum rate, kg/ha	II	$y = 43.6 + 0.0047x$	10	0.88	<0.001
K, µg/g	Gypsum rate, kg/ha	I	$y = 0.434 - 0.0000037x$	10	0.62	0.0070
K, µg/g	Gypsum rate, kg/ha	II	$y = 0.273 - 0.0000022x$	10	0.56	0.0126
pH_s¶	Gypsum rate, kg/ha	I	$y = 3.88 + 0.0000052x$	5	0.81	0.0386
pH_s#	Gypsum rate, kg/ha	I	$y = 3.83 + 0.0000035x$	5	0.90	0.0138
Ca, µg/g	Gypsum rate, kg/ha	I	$y = 156 + 0.0168x$	5	0.98	0.0009
Ca, µg/g	Gypsum rate, kg/ha	I	$y = 168 + 0.127x$	5	0.97	0.0023
Al, µg/g	Gypsum rate, kg/ha	I	$y = 354 - 0.0016x$	5	0.74	0.0630

† pH_s, pH in 0.01 *M* $CaCl_2$.
‡ TCE, total $CaCO_3$ equivalent.
§ EC, electrical conductivity.
¶ 15–30 cm depth.
# 30–45 cm depth.

Table 5. Statistical significance of regressions describing the relationships of plant nutrient concentrations and dry matter yield (y) with soil and plant parameters (x) during Phase I (establishment) and Phase II (production) on a Gilpin silt loam (Typic Hapludults) in southern West Virginia receiving surface-applied treatments of gypsum, limestone, and MgO to facilitate establishment and production of tall fescue and orchardgrass.

y†	x	Phase	Relationship	n	r^2	P
Ca, g/kg	Ca saturation, %	I	$y = 3.74 + 4.08x$	10	0.63	0.006
Ca, g/kg	Ca saturation, %	II	$y = 1.71 + 4.62x$	10	0.92	<0.0001
Mg, g/kg	Soil Mg, μg/g	I	$y = 0.74 + 0.0878x$	10	0.67	0.0037
Mg, g/kg	Soil Mg, μg/g	II	$y = 1.137 + 0.0155x$	10	0.88	<0.0001
S, g/kg	Soil S, μg/g	I	$y = 2 + 0.00472x - 0.00000242x^2$	10	0.87	0.0009
S, g/kg	Soil S, μg/g	II	$y = 2.38 + 0.00735x$	10	0.80	0.0005
S, g/kg	Gypsum rate, kg/ha	I	$y = 2.37 + 0.000067x$	10	0.76	0.0009
S, g/kg	Gypsum rate, kg/ha	II	$y = 2.69 + 0.0000357x$	10	0.76	0.001
P, g/kg	Gypsum rate, kg/ha	I	$y = 1.964 + 0.0000168x$	10	0.68	0.0033
K, g/kg	Gypsum rate, kg/ha	I	$y = 17.09 + 0.000148$	10	0.83	0.0003
DMY, kg/ha	pH_s	I	$y = 45\,975 - 22\,740x + 2\,918x^2$	10	0.70	0.0147
DMY, kg/ha	pH_s	II	$y = 822 + 1\,619x$	10	0.68	0.0035
DMY, kg/ha	Al saturation	I	$y = 3\,130 - 4\,930x + 4\,182x^2$	10	0.85	0.0014
DMY, kg/ha	Al saturation	II	$y = 8\,991 - 4\,569x + 3\,034x^2$	10	0.63	0.0306
DMY, kg/ha	Plant K, g/kg	I	$y = -1\,486 + 199.4x$	5	0.89	0.0153
DMY, kg/ha	Plant P, g/kg	I	$y = -1\,403 + 1711x$	5	0.91	0.0111

† Plant nutrient concentration and dry matter yield (DMY) as related to changes in x.

nutrient sufficiency levels for orchardgrass given by Jones et al. (1991), assuming that they would be reasonable guides for evaluating both Phase I and II forage nutrient concentrations.

Soil pH and Aluminum

In general, the addition of dolomitic limestone, MgO, $Mg(OH)_2$, and by-product gypsum (with a $CaCO_3$ equivalent of 5%) increased mean Phase I and II pH_s in proportion to the TCE of the added materials (Fig. 3). Extractable soil Al was negatively correlated with soil pH_s and decreased as treatment TCE increased (Table 4).

A deviation from the general trend of increasing pH_s with increasing TCE was observed for treatment G_1L (Fig. 3). Adding 1000 kg/ha gypsum to treatment G_0L significantly lowered Phase I pH_s from 4.33 to 4.18 and increased ($P = 0.08$) Phase I Al from 141 to 177 μg/g (Table 6). Acidity enhancement from moderate application rates of gypsum may have implications when farmers apply ordinary superphosphate fertilizer, which contains about 50% gypsum; adding ordinary superphosphate at rates recommended for alfalfa and clover seedling establishment on P-deficient soils (West Virginia Univ., 1982) would supply 1495 kg/ha gypsum. Decreases in soil pH_s resulting from small additions of gypsum have been previously observed (Clark et al., 1995b). Slight yield decreases at low gypsum rates have also been noted (Clark et al., 1994; Wright et al., 1989). In a Brazilian Ultisol, incorporating gypsum at similar rates increased soil solution Al by 80% although large proportions of the Al were present as a nontoxic aluminum sulfate complex (Pavan et al., 1982). In our case, the increased Al may also have been nontoxic because yields did not decrease (Table 7).

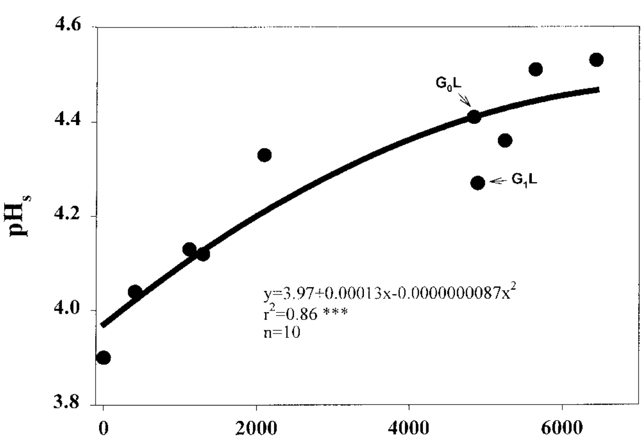

Fig. 3. Mean Phase I and Phase II soil pH in 0.01 M $CaCl_2$ (pH_s) as affected by total $CaCO_3$ equivalency (TCE) of amendments surface-applied to a Typic Hapludults in southern West Virginia. Treatment G_0L received limestone, and treatment G_1L received limestone and 1000 kg/ha by-product gypsum. Coefficient-of-determination significance of $P < 0.001$ indicated by *.**

The detrimental effects on pH and Al that occurred when 1000 kg/ha gypsum was added to treatment G_0L were not evident when 16 000 and 32 000 kg/ha gypsum were applied (Table 6). It is interesting to note that the 1000 kg/ha gypsum used in treatment G_1L is roughly equivalent to the amount that would be soluble in the soil solution in the top 15 cm of soil at field capacity moisture content. One could hypothesize that the decrease in pH_s in the 1000 kg/ha gypsum treatment was associated with saturation of the soil solution with gypsum; while, at higher rates of addition, residual liming agents [probably $Ca(OH)_2$ or $CaCO_3$] present in the by-product gypsum material increased pH_s, precipitated Al, and overcame pH-depressing effects associated with small gypsum applications. This might explain why yield depression induced at low gypsum rates disappeared when higher rates of gypsum were added in experiments conducted by Clark et al. (1994).

Magnesium

Soil Mg levels were already deficient in our abandoned pasture; Mg concentration in treatment G_0 during the study averaged about half of the 50 μg/g level that West Virginia University considers deficient (van Eck, 1990) (Fig. 4). Adding gypsum further decreased soil Mg. Gypsum-induced Mg loss has been noted frequently (Shainberg et al., 1989) and is associated with displace-

Table 6. Extractable element concentrations, Al saturation (Alsat), electrical conductivity (EC), and pH of the 0- to 15-cm depth of a Typic Hapludults in southern West Virginia that received surface applications of gypsum, dolomitic lime, and MgO (described in Table 1).

Treatment	Mg	K	Al	Alsat	EC	pH_s†
	μg/g			%	dS/m	
			Phase I			
G_0L	147	163	141	27.8	0.11	4.33
G_1L	114	171	177	34.3	0.14	4.18
G_8L	89	183	123	21.1	0.24	4.34
$G_{16}L$	57	136	102	13.6	0.57	4.41
$G_{32}L$	42	125	109	11.5	0.85	4.42
G_0	33	177	249	59.4	0.10	3.85
G_0MgO	132	168	197	50.4	0.11	4.09
G_8	20	153	230	38.4	0.37	4.05
G_8MgH	52	139	196	36.6	0.26	4.11
$G_{16}MgO$	76	152	152	28.7	0.37	4.30
LSD‡	27	27	40	8.0	0.17	0.13
			Phase II			
G_0L	129	102	123	25.4	0.12	4.50
G_1L	110	104	141	29.7	0.11	4.35
G_8L	67	102	127	33.0	0.13	4.39
$G_{16}L$	80	77	87	17.9	0.16	4.62
$G_{32}L$	54	84	85	14.5	0.52	4.64
G_0	22	104	245	63.3	0.08	3.95
G_0MgO	117	119	206	50.9	0.09	4.14
G_8	12	105	227	55.1	0.12	4.02
G_8MgH	23	95	200	48.1	0.13	4.14
$G_{16}MgO$	91	98	134	28.0	0.15	4.36
LSD‡	21	20	36	8.0	0.12	0.16

† pH_s, pH in 0.01 *M* $CaCl_2$.
‡ *F*-protected LSD at $P = 0.05$.

ment of Mg by Ca, followed by leaching. Magnesium ions form uncharged ion pairs with SO_4 (Bohn et al., 1979) that quickly move through soils with minimum sorption.

Use of dolomitic limestone, $Mg(OH)_2$–enriched gypsum, or MgO fertilizer prepared by lightly calcining $MgCO_3$ helped maintain adequate Mg levels. Adding 268 kg/ha Mg as MgO fertilizer (treatments G_0MgO and

Table 7. Annual dry matter yield (DMY) and plant nutrient concentrations as affected by treatments of gypsum, dolomitic lime, and MgO (described in Table 1), and upper and lower sufficiency levels for orchardgrass plant mineral concentrations as given by Jones et al. (1991). Dry matter yields are calculated from four harvests in Phase I (establishment phase) and six harvests in Phase II (production phase).

Treatment	DMY	Ca	Mg	S	P	K
	kg/ha	g/kg plant dry weight				
			Phase I			
G_0L	1802	*4.74*†	1.89	2.31	*1.91*	*17.5*
G_1L	1881	*4.81*	1.74	2.10	*1.86*	*16.2*
G_8L	2168	6.21	*1.22*	2.46	*2.19*	*18.3*
$G_{16}L$	2597	6.90	*1.17*	3.56‡	2.32	*20.0*
$G_{32}L$	2653	6.64	*0.87*	4.36	2.31	*20.9*
G_0	1629	*4.91*	*1.40*	2.16	*1.87*	*16.8*
G_0MgO	1751	*4.70*	2.35	2.41	*1.94*	*16.4*
G_8	1829	5.95	*0.94*	3.72	*2.13*	*18.8*
G_8MgH	2077	5.85	*1.36*	3.37	*2.16*	*18.9*
$G_{16}MgO$	2246	7.50	*1.11*	3.31	2.44	*20.3*
LSD§	585	1.08	0.25	0.40	0.24	2.76
			Phase II			
G_0L	7643	*3.81*	2.98	2.97	4.21	34.5
G_1L	7937	*3.68*	2.80	2.79	4.03	32.4
G_8L	8164	*4.16*	2.38	2.97	4.00	31.1
$G_{16}L$	8623	*4.60*	2.21	3.10	4.19	32.3
$G_{32}L$	8310	5.34	1.90	3.99	4.33	32.2
G_0	7408	*2.76*	*1.48*	2.31	3.26	29.2
G_0MgO	7531	*2.64*	3.41	2.95	4.33	32.9
G_8	6994	*3.92*	*1.18*	2.97	4.09	32.6
G_8MgH	7762	*3.65*	1.73	2.85	3.86	31.7
$G_{16}MgO$	7640	*4.18*	2.19	3.16	4.02	30.8
LSD§	663	0.70	0.45	0.54	0.80	5.53
Upper sufficiency limit		9.00	3.00	2.50	3.50	35.0
Lower sufficiency limit		5.00	1.50	2.00	2.30	26.0

† Values in italics are less than the lower limit for *sufficient* given by Jones et al. (1991) for orchardgrass.
‡ Underlined values are greater than the upper limit for *sufficient* given by Jones et al. (1991) for orchardgrass.
§ *F*-protected LSD at $P = 0.05$.

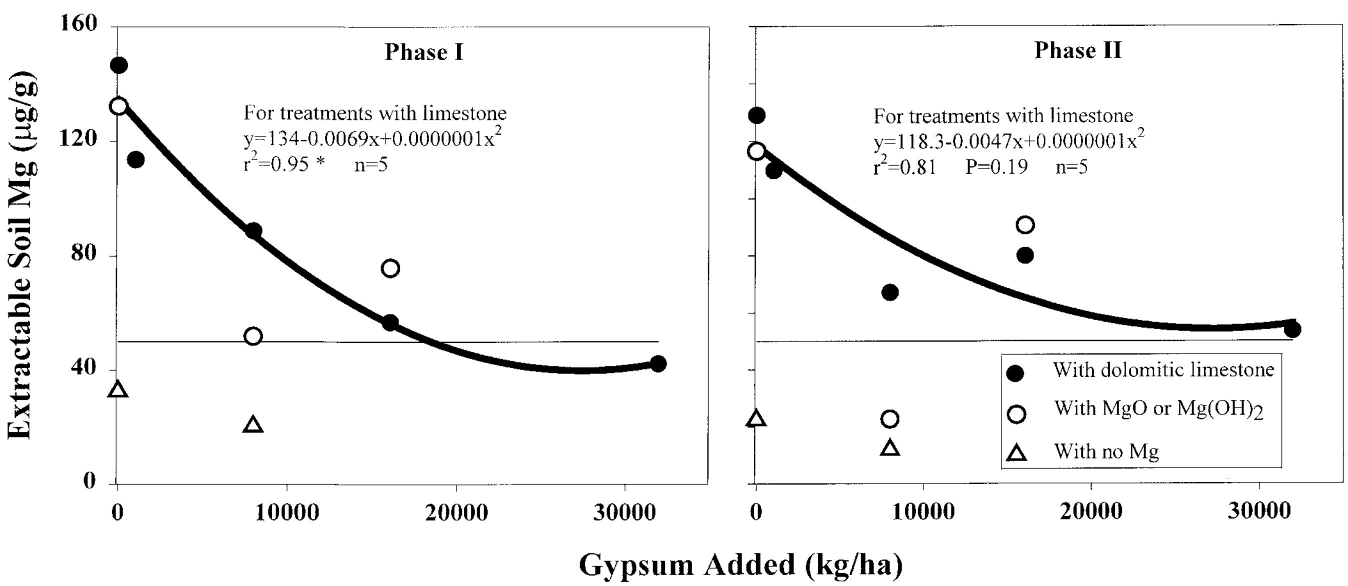

Fig. 4. Extractable soil Mg as affected by levels of gypsum surface-applied to an abandoned pasture on a Typic Hapludalfs soil during establishment (Phase I) and production (Phase II). Horizontal line indicates the level considered deficient by West Virginia University (van Eck, 1990). Coefficient-of-determination significance of $P < 0.05$ indicated by *.

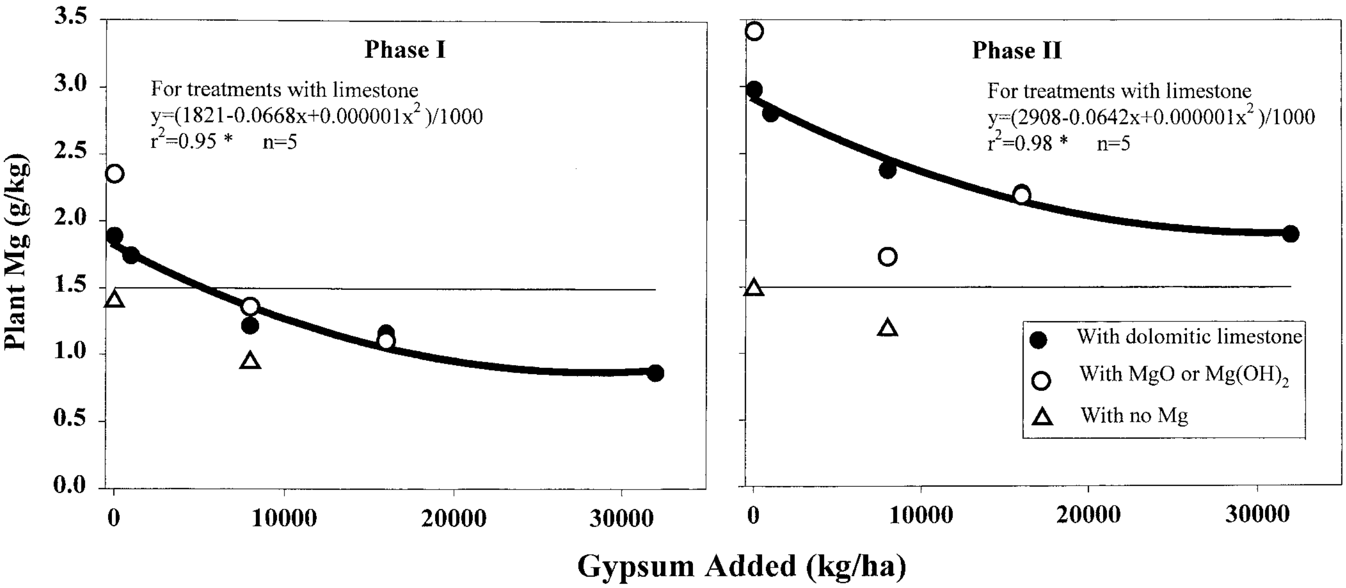

Fig. 5. Forage Mg concentrations as affected by levels of gypsum surface-applied to an abandoned pasture on a Typic Hapludalfs soil in southern West Virginia. Horizontal line indicates the level considered low by Jones et al. (1991). Coefficient-of-determination significance of $P < 0.05$ indicated by *.

G_{16}MgO) increased soil Mg levels to about the same level as adding almost twice as much Mg in the form of dolomitic limestone (Fig. 4; Table 6). Application of 195 kg/ha Mg as $Mg(OH)_2$–enriched gypsum (treatment G_8MgH) significantly increased Phase I soil Mg concentrations compared with treatment G_8 (Table 6), but in Phase II, the benefit had largely disappeared.

Plant Mg concentrations generally reflected changes in soil Mg concentrations resulting from gypsum and Mg amendments (Fig. 5). Based on net increases in both soil and plant Mg levels induced per unit of Mg added to soil (Table 8), MgO was at least 60% more effective than dolomitic limestone while $Mg(OH)_2$ in the Mg-enriched gypsum by-product, except for Phase II soil, was approximately equal in efficiency to dolomitic limestone.

Sulfur

Levels of soil S were highly correlated with amounts of gypsum added and with soil electrical conductivity and soil Ca (Table 4). Plant S was proportional to amount of gypsum applied and to soil S levels (Table 5). The 1000 kg/ha gypsum rate (treatment G_1L) was included in this experiment to determine if forage production would respond to S additions. Apparently, soil supplies of S were adequate because the lowest forage concentration of S we observed was 2.1 g/kg, which is above the level of 1.9 g/kg considered low for orchardgrass (Table 7).

Potassium and Phosphorus

The amount of K in the surface 0- to15-cm soil layer was negatively affected by levels of added gypsum (Table 4). Negative effects of gypsum on soil K levels have been observed (Shainberg et al., 1989) but to a lesser extent than negative effects on Mg (van Raij, 1992). The accepted explanation for lowered soil K levels is displacement of K^+ ions from soil exchange sites and subsequent leaching of K out of the rooting zone. In Phase I, however, regression of increases in plant K uptake against decreases in soil exchangeable K content (calculated from Tables 6 and 7) showed that 18% of the decrease in soil K was attributable to K taken up into harvested plant tissue.

Concentrations of K and P in Phase I plant tissue

Table 8. Effects of Mg source and gypsum rate on increase in exchangeable soil Mg (0–15 cm layer) per unit added Mg and plant recovery of added Mg, based on comparisons between treatments G_0L and G_0, G_8L and G_8, G_0Mg and G_0 and G_8MgH and G_8 for amendments surface-applied to a Typic Hapludults in southern West Virginia during establishment (Phase I) and production (Phase II).

		Increase in extractable soil Mg†		Plant recovery of added Mg‡	
Source of Mg	Level of gypsum	Phase I	Phase II	Phase I	Phase II
	kg/ha	(kg/ha Mg increase)/(kg/ha added Mg)		(kg/ha Mg increase)/(kg/ha added Mg)	
Dolomitic limestone	0	0.50b§	0.47b	0.002a	0.016b
Dolomitic limestone	8000	0.30b	0.24c	0.002a	0.022b
MgO	0	0.92a	0.75a	0.008a	0.055a
$Mg(OH)_2$	8000	0.36b	0.13c	0.006a	0.027b

† Calculated as $(Mg_1 - Mg_0)/(Mg_{added})$ where Mg_1 = extractable soil Mg in treatment with added Mg, Mg_0 = extractable soil Mg in treatment without added Mg, and Mg_{added} = amount of amendment Mg added.

‡ Calculated as $[(Conc_1)(DMY_1) - (Conc_0)(DMY_0)]/(Mg_{added})$ where $conc_1$ and $conc_0$ refer to Mg concentrations in harvested forage with and without added Mg, respectively; DMY_1 and DMY_0 refer to dry matter yields in treatments with and without added Mg, respectively; and Mg_{added} = amount of amendment Mg added.

§ Within a column, values followed by different letters are significantly different at $P = 0.05$ level using *F*-protected LSD.

increased as the amount of gypsum added increased (Table 5), which was beneficial because these elements were present at less than the sufficiency level for orchardgrass in most treatments in Phase I (Table 7). Because there was no statistically significant relationship between plant K or P concentration and treatment TCE, nor with the resulting increase in soil pH_s, it appears that the beneficial effect of by-product gypsum on K and P acquisition was not associated with potential to neutralize soil acidity but was associated with the $CaSO_4$ component. The effect was not attributable to K or P in the gypsum by-product either because the material contained only 32 and 61 μg/g of these nutrients (Clark et al., 1995a), which would contribute <2 kg/ha K or P. Gypsum may have reduced activity of Al^{3+} at root surfaces, which could promote more rapid root growth, improve mycorrhizae development, or allow finer root branching, all of which could in turn increase K and P uptake.

Meeting Cattle Mineral Nutrition Requirements

Beef cattle (*Bos taurus*) need dietary levels of 6 to 30 g/kg K, 1 to 4 g/kg Mg, 1.9 to 7.3 g/kg Ca, and 1.2 to 3.4 g/kg P, depending on age and condition (Natl. Res. Counc., 1996). Soil treatment with 16 000 kg/ha or more gypsum improved the nutritive value of dry matter harvested during Phase I in terms of Ca, P, and K concentrations (Table 7). In Phase II, K and P levels in most treatments were sufficient for beef cattle, even without addition of gypsum; however, the increase in Ca concentration from gypsum addition improved feed value. On the other hand, gypsum had a negative effect on Phase I Mg levels, and concentrations in treatments G_8 and $G_{32}L$ fell below the minimum recommendation. In Phase II, forage Mg was above the minimum for all treatments. Concentrations of S in forage at the highest rate of gypsum application reached 4.4 g/kg in Phase I.

Treatment Effect on Dry Matter Yield

Overall, Phase II dry matter yield was nearly four times greater than in Phase I (Table 7), reflecting the establishment of responsive forage species and increased fertilizer applications. Treatment × year interactions were not significant in Phase I or Phase II, so mean yield data are presented. Highest yields were observed in the two highest limed gypsum treatments.

In general, yields increased in proportion to effects of amendments in overcoming soil acidity, as illustrated by the relationship with decreased soil Al (Fig. 6). Yields were also correlated with pH_s and Al saturation [Al/(Ca + Mg + K + Al)].

We estimated the specific effect of dolomitic limestone on yield by comparing yields observed in treatments G_0MgO, G_8MgH, and $G_{16}MgO$ (no added limestone) with yields in treatments G_0L, G_8L, and $G_{16}L$ (with 4650 kg/ha limestone). Each treatment received ample Mg (at least 195 kg/ha). Mean yield benefit per 1000 kg/ha increase in TCE was 45 and 135 kg/ha in Phase I and Phase II, respectively.

Effects of gypsum addition were estimated by evaluating treatments G_0L, G_1L, G_8L, $G_{16}L$, and $G_{32}L$ (Fig. 7). Increases in dry matter yield from gypsum application were described by quadratic relationships (Phase I $r^2 = 0.98$, $P = 0.02$, and $n = 5$ and Phase II $r^2 = 0.93$, $P = 0.07$, and $n = 5$). These relationships indicated

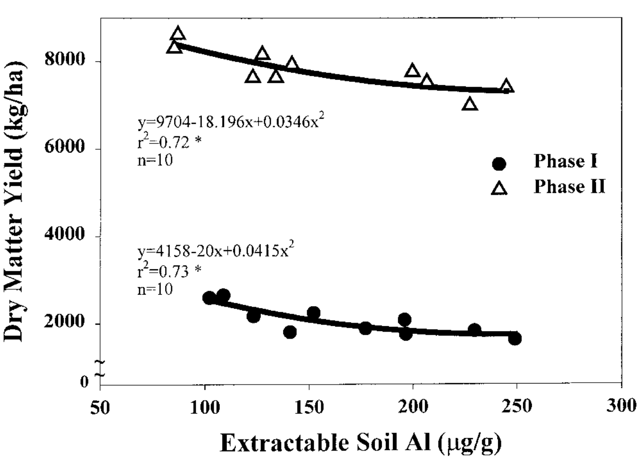

Fig. 6. Forage dry matter yield during establishment (Phase I) and production (Phase II) as a function of extractable soil Al in a Typic Hapludults receiving surface-applied gypsum, limestone, and MgO. Coefficient-of-determination significance of $P < 0.05$ indicated by *.

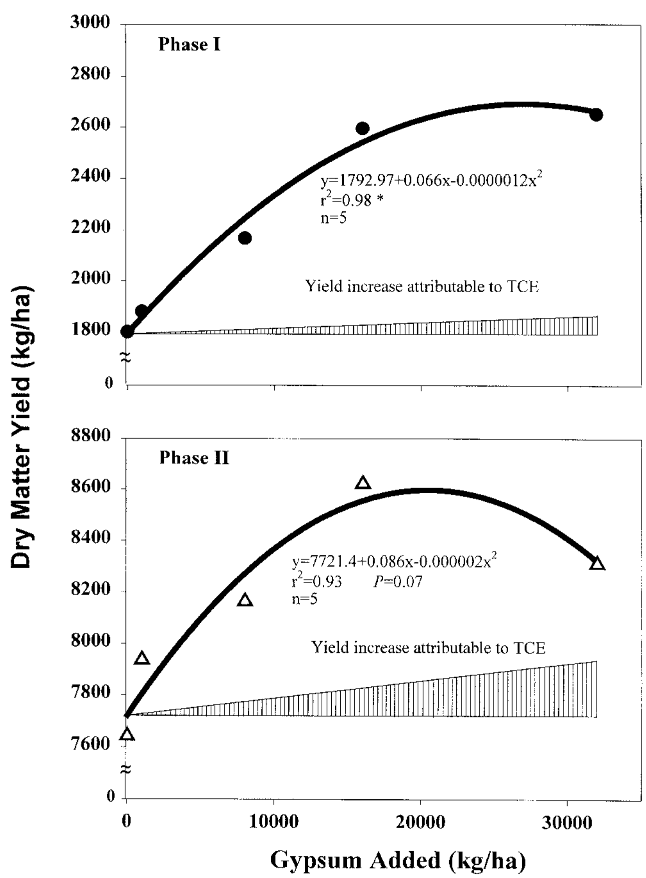

Fig. 7. Annual forage dry matter yield during establishment (Phase I) and production (Phase II) as a function of level of surface-applied by-product gypsum for treatments receiving 4650 kg/ha dolomitic limestone, and estimated portion of yield attributable to total $CaCO_3$ equivalency (TCE) arising from liming constituents in by-product gypsum. Coefficient-of-determination significance of $P < 0.05$ indicated by *.

maximum yield responses would occur with additions of between 20 000 and 30 000 kg/ha gypsum.

A small part of the yield improvement from gypsum may have been due to effects of acidity-neutralizing materials present in the by-product (equivalent to 5 g of $CaCO_3$ per 100 g of amendment). We estimated the contribution to yield of TCE from by-product gypsum by using the mean yield increases from dolomitic limestone application, based on the assumption that the neutralizing constituent in the gypsum by-product was equally effective as dolomitic limestone. Only 4% (Phase I) and 11% (Phase II) of the yield improvement between treatments G_0L and $G_{16}L$ could be explained by the increase in TCE associated with nongypsum liming materials contained in the 16 000 kg/ha by-product added (Fig. 7).

Additional yield improvements not explainable by TCE could have been caused by failure of our assumption that neutralizing material present in the gypsum by-product was equal to that in dolomitic limestone. The material in gypsum might have been more effective than dolomitic limestone, perhaps due to smaller particle size or different chemical composition (Barber, 1967). However, a more likely alternative explanation is that yield improvement occurred because of enhanced mineral nutrient uptake due to reduced Al phytotoxicity. Gypsum can decrease Al concentrations at root surfaces by increasing positive charge there (Kinraide et al., 1994) and can reduce soil solution activities of toxic trivalent Al by promoting formation of nontoxic aluminum sulfate complexes (Pavan et al., 1982).

Phase I yields in the five limed gypsum treatments were highly correlated with plant K and P (Table 5). This, and the observed increases in plant P and K concentrations with gypsum level, but not with amendment TCE, support the argument that gypsum itself had beneficial effects on nutrient uptake, perhaps through promotion of deeper, finer, or more vigorous roots. In Phase I, subsoil pH_s and Ca values in the 15- to 30- and 30- to 45-cm soil layers were positively correlated with the amount of gypsum added, and soil Al at 15 to 30 cm was negatively correlated ($P = 0.06$) (Table 4). These gypsum-induced changes would have made subsurface soil conditions more hospitable to deeper plant root growth (Feldhake and Ritchey, 1996).

Annual yield increases predicted from the gypsum response relationship (Fig. 7) for the application of 16 000 kg/ha gypsum were 42% (748 kg/ha forage) in Phase I and 11% (835 kg/ha forage) in Phase II. This represents gross income increases of $60 and $67 per hectare based on typical grass hay values of $80 per 1000 kg. Each 1000 kg/ha gypsum applied thus increased annual returns per hectare by $3.75 and $4.19 for Phases I and II, respectively. In comparison, each 1000 kg/ha TCE as dolomitic limestone in our study increased annual returns per hectare by $3.60 and $10.80.

We conclude that adding gypsum in the presence of dolomitic limestone in a pasture renovation program improved yields but adding gypsum alone adversely affected soil and plant Mg concentrations although yields were not depressed. Use of dolomitic limestone or MgO fertilizer prepared from lightly calcined magnesite helped reduce gypsum-induced Mg deficiencies. Tall fescue responded more to decreased soil acidity than did orchardgrass. The by-product gypsum used in this experiment had some acidity-neutralizing components that contributed to yield increases, but the greater part of the yield improvements were correlated with improved plant uptake of P and K.

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